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Dynamical Stability and Environmental Influences in Low Surface Brightness Disk Galaxies

J. Christopher Mihos,[1,2] Stacy S. McGaugh[3], and W.J.G. de Blok[4]

ABSTRACT

Using analytic stability criteria, we demonstrate that, due to their low surface mass density and large dark matter content, LSB disks are quite stable against the growth of global nonaxisymmetric modes such as bars. However, depending on their (poorly constrained) stellar velocity dispersions, they may be only marginally stable against local instabilities. We simulate a collision between an LSB and HSB galaxy and find that, while the HSB galaxy forms a strong bar, the response of the LSB disk is milder, manifesting weaker rings and spiral features. The lack of sufficient disk self-gravity to amplify dynamical instabilities naturally explains the rarity of bars in LSB disks. The stability of LSB disks may also inhibit interaction-driven gas inflow and starburst activity in these galaxies.

Subject headings: galaxies:evolution, galaxies:interactions, galaxies:kinematics and dynamics, galaxies:spiral, galaxies:starburst, galaxies:structure

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[1]Hubble Fellow

[2]Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218; hos@pha.jhu.edu

[3]Carnegie Institute of Washington, Department of Terrestrial Magnetism, 5241 Broad Branch Road, NW, Washington, DC 20015; ssm@dtm.ciw.edu

[4]Kapteyn Astronomical Institute, P.O. Box 800, 9700 AV Groningen, The Netherlands; blok@astro.rug.nl

1. Introduction

Low surface brightness (LSB) disk galaxies represent a common product of galaxy formation and evolutionary processes. Recent surveys have uncovered large numbers of LSB galaxies (e.g., Schombert et al. 1992) whose central surface brightnesses are an order of magnitude fainter than in their high surface brightness (HSB) counterparts. These LSB galaxies can rival HSB galaxies in terms of size and luminosity, and are estimated to contain as much as one-third of the total mass in galaxies in the local universe (McGaugh 1996). They are rich in HI and are forming stars at a very low rate, leading to the suggestion that LSB galaxies represent relatively unevolved systems (McGaugh & Bothun 1994; de Blok et al. 1995) whose surface densities are too low to foster the dynamical processes which may lead to star forming activity (van der Hulst et al. 1993).

The paucity of star formation in LSB disks may also be linked to their local environment. Although embedded in the same large scale structure as HSB galaxies, LSB galaxies are less clustered on all scales (Mo et al. 1994) and are particularly isolated on scales smaller than a few Mpc (Zaritsky & Lorrimar 1992; Bothun et al. 1993). Without the well-established dynamical trigger provided by an interacting companion, LSB galaxies may simply evolve passively due to their low surface densities, and never experience any strong star-forming era in their lifetimes. Indeed, sufficient tidally induced star formation in LSB disks may drive evolution from LSB to HSB galaxies. This has been suggested as the cause of the observed isolation of LSB galaxies: interactions in denser environments transform them into HSB galaxies or perhaps even destroy them entirely.

Dynamical modeling has shown that the ability for interactions to trigger strong starbursts is linked to the onset of bar instabilities in the stellar disk (e.g., Noguchi 1987; Barnes & Hernquist 1991; Mihos et al. 1992; Mihos & Hernquist 1994ab, 1996) – instabilities which are largely governed by the internal structure of disk galaxies. However, these efforts employed model galaxies constructed to match typical HSB galaxies, and recent work has shown that the structural properties of LSB galaxies are significantly different (de Blok & McGaugh 1996; hereafter dBM). In particular, LSB galaxies have lower disk mass densities, more slowly rising rotation curves, and a higher fraction of dark to visible matter than do HSB galaxies. As a result, the strong bar-induced inflows and starburst activity manifested in numerical simulations and observed in bright nearby interacting systems may not typify the response of LSB galaxies to a gravitational interaction.

The degree of stability of LSB disks could determine to a great extent exactly how any collisionally-induced evolution would occur. Bars are rare in LSB galaxies; of the 36 late type LSB galaxies in the studies of McGaugh & Bothun (1995) and de Blok et al. (1995), only one (F577-V1) shows a strong bar. Similarly, a perusal of the LSB catalog by Impey

et al. (1996) shows only ~ 20 barred systems out of a sample of ~ 500 LSBs. This frequency of bars is much lower than the $\sim 30\%$ found for the field HSB galaxies which make up the RC2 catalog (Elmegreen, Elmegreen, & Bellin 1990). It is unclear, however, if the scarcity of barred LSBs is due to their isolation or to a higher degree of disk stability in LSB disks.

In this letter, we explore the dynamical stability of LSB disks in order to judge their response to external perturbations. Both analytic stability criteria and numerical simulations are used. We find that LSB disks are more stable against bar formation than their HSB counterparts, but that collisions may drive local instabilities in LSB disks. We close with a discussion of our results in the context of collisionally induced galaxy evolution.

2. Structure of LSB Disks

The rotation curves of LSB disks exhibit two general characteristics. The first is a rigorous adherence to the Tully-Fisher relation (Sprayberry et al. 1995; Zwaan et al. 1995; Hoffman et al. 1996) so that galaxies of the same luminosity have the same rotation velocity in the flat, outer part of the rotation curve. The second is a dependence of the rate of rise of the inner part of the rotation curve on the surface brightness (de Blok et al. 1996). This occurs in the obvious sense, with more diffuse galaxies having more gradually rising rotation curves. This difference becomes much less pronounced when the radius is normalized by the scale length — $V(R/h)$ is generally quite similar at a given luminosity (e.g., Persic & Salucci 1996), though some difference often remains.

These properties have a striking consequence: lower surface brightness galaxies are progressively more dark matter dominated (de Blok et al. 1996, de Blok & McGaugh 1997). Rotation curve decompositions indicate that the decreased surface brightness in LSB disks is accompanied by a decrease in mass surface density of the disk. Since it is the disk self gravity which drives instabilities, the dark matter domination of LSB galaxies may lead to important differences in their response to perturbations.

Here we examine models motivated by two galaxies with comparable luminosities but surface brightnesses differing by nearly 3 magnitudes: NGC 2403 and UGC 128 (dBM). The rotation curve for UGC 128 is typical of rotation curves for a large sample of LSB disks by de Blok et al. (1996; see their Figure 7). We decompose the rotation curves into disk and halo components assuming "maximum disk," where we attribute as much mass to the stellar disk as allowed by the rotation curves. Under this assumption, the disk surface density of UGC 128 is nearly an order of magnitude lower than that of NGC 2403, roughly comparable to the 2.8 B magnitude difference in central surface brightness. With

the shorter radial scale length for NGC 2403 (2.1 kpc vs. 6.8 kpc for UGC 128), the two galaxies have very similar total disk masses.

It is far from obvious that the maximum disk solution is plausible in LSB galaxies (see de Blok & McGaugh 1997 for an extensive discussion). In the case of UGC 128, maximum disk gives $M/L_B = 3$ for the stars, 2 or 3 times what is reasonable from the standpoint of stellar populations (McGaugh & Bothun 1994; de Blok et al. 1995). Nonetheless, we retain the maximum disk solution because it is a conservative starting point for our analysis: if the actual disks are less massive than we assume, they will be even more stable than we find.

3. Analytic Stability Criteria

Given the rotation curve decomposition from dBM (see their Table 1), we can now calculate a variety of disk stability parameters to examine quantitatively the issue of LSB disk stability. Although the rotation curves are not well constrained at large radius (i.e. at R > 5 scale lengths), it is the stability and mass distribution in the inner few scale lengths in which we are ultimately interested. LSBs are predominantly stellar in this region even though they can have quite high gas contents at larger radii. Uncertainties in the mass distribution at large radius will have little effect on the evolution of the inner disk. The rotation curves of NGC 2403 and UGC 128 are shown in Figure 1a.

Many criteria have been proposed to describe the global stability of disk galaxies (e.g.,

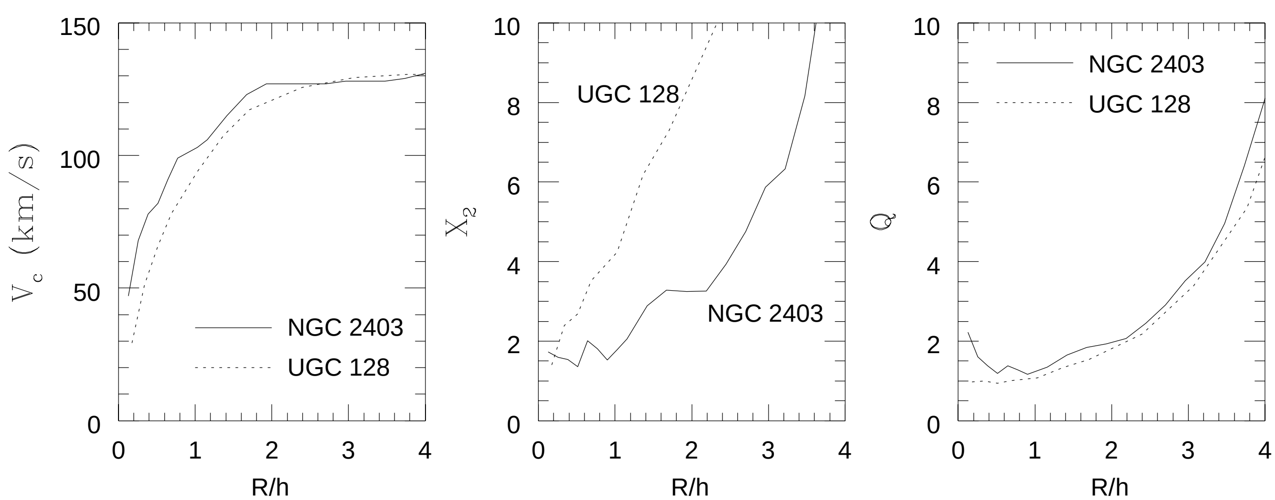

Fig. 1.— Left: Rotation curves of NGC 2403 (HSB) and UGC 128 (LSB), as a function of disk scale length (R/h). Middle: X_2 stability parameter. Right: Toomre Q parameter. The two curves for UGC 128 reflect two choices for σ_r.

Ostriker & Peebles 1973; Efstathiou et al. 1982; Christodoulou et al. 1995). Regardless of the details of implementation, the fundamental argument behind these varying criteria is that the presence of a massive dark matter halo helps to stabilize galaxies against bar formation (as long as the dark matter is dynamically hot). LSB disks, with their very low surface mass density and high dark matter contents (dBM; de Blok & McGaugh 1997), should be much more stable than their HSB counterparts.

One measure of the susceptibility of galactic disks to global nonaxisymmetric instabilities is the X parameter (e.g., Goldreich & Tremaine 1978, 1979; Toomre 1981):

$$X_m \equiv \frac{k_{crit} R}{m} = \frac{\kappa^2 R}{2\pi m G \Sigma_d},$$

where k_{crit} is the wavenumber of marginal stability, κ is the epicyclic frequency, R is the radius, Σ_d is the disk surface density, and $m = 2$ for bar modes. Toomre (1981) showed that for flat rotation curves, disks proved stable against growing modes if $X > 3$, while for linearly rising rotation curves $X > 1$ is a sufficient condition for stability (A. Toomre, private communication). Nonetheless, galaxies with slowly rising rotation curves are believed to be prone to bar formation due to two effects: their lowered epicyclic frequency reduces X, and their large region of solid body rotation suggests that, once formed, bars may exist for many dynamical times (Lynden-Bell 1979). The slowly rising rotation curves of LSB disks thus suggests that they may be susceptible to the growth of global modes in the disk. However, their lowered mass surface density works in the opposite sense, and it is the competition between these two effects which determines their overall stability.

Given the rotation curve decomposition and mass modeling from dBM, we can calculate the X_2 parameter for NGC 2403 and UGC 128 (note that the $m = 2$ bar mode is the strongest non-axisymmetric instability in most disk galaxies). Figure 1b shows X_2 as a function of radial scale length for these two galaxies. The high surface brightness galaxy NGC 2403 is only marginally stable over a large range of radius: in the inner regions $X \sim 1.5 - 2$, while at two scale lengths, where the rotation curve has flattened, $X \sim 3$, still close to instability. By contrast, the low surface brightness galaxy UGC 128 proves stable throughout the disk, due to its lower mass surface density. We emphasize that we have used maximum disk models; if LSBs are less than maximal disks, they will be even *more* stable.

If LSB disks are stable against the growth of global instabilities in the disks, are they also stable against *local* instabilities? The growth of local axisymmetric instabilities is measured by Toomre's Q parameter (Toomre 1964),

$$Q \equiv \frac{\sigma_r \kappa}{3.36 G \Sigma_d},$$

where σ_r is the radial velocity dispersion of the disk stars. The determination of Q is more problematic than X_2, because of the explicit dependence on σ_r. Velocity dispersions in LSB disks have not been directly measured, due to their very low surface brightness nature. If LSB disks have velocity dispersions comparable to HSB disks, they will be quite stable due to their lowered disk surface mass density. Alternatively, if stellar velocity dispersions are linked to mass surface density, Q for HSB and LSB disks may be similar. In this case, LSBs are globally stable against bars, but may only be marginally stable to local perturbations. For example, Figure 1c shows Q in each disk, assuming $\sigma_r = 30$ km s^{-1} for NGC 2403 (similar to the value in the solar neighborhood; Mihalas & Binney 1981) and that velocity dispersion and surface density follow the relation $\sigma^2 \sim \Sigma_d$ as might be expected from simple energy arguments. While velocity dispersion most likely varies with radius, these arguments suggest that LSB and HSB disks may have similar *local* stability properties, and that local instabilities might grow in LSB disks where global modes cannot. This result is is similar to that of van der Hulst et al. (1993), who found the gas in LSB galaxies was only marginally stable against local instabilities.

4. Dynamical Modeling

The analytic arguments of §3 indicate that LSB disks will be quite stable against bar formation, but perhaps susceptible to local instabilities in the disk. These arguments are based largely on linear perturbation theory, however, and it is unclear just how LSB disks would respond to a strong perturbation such as an interaction with a neighboring galaxy. To examine this situation, we use numerical simulation to model a grazing encounter between an LSB galaxy and an HSB companion. We choose a zero-energy parabolic orbit, with a perigalactic separation of $R_p = 10$ disk scale lengths. The collision is perfectly prograde, maximizing the tidal effects acting on the galaxy disks.

Rather than build galaxy models which differ in a number of structural parameters, we focus on variations in disk surface density to define the difference between HSB and LSB disk galaxies. We begin with a fiducial composite disk/halo galaxy model for the HSB galaxy, built as described by Hernquist (1993). This model consists of a stellar disk of mass $M_d = 1$ and exponential scale length $h = 1$, and a truncated isothermal dark matter halo of mass $M_h = 5.8$, core radius $\gamma = 1$, and exponential cutoff radius $r_c = 10$. In these units, the (disk) half-mass rotation period is 13 time units. To construct the LSB galaxy, we use the same set of structural parameters, except that the disk mass is chosen to be $M_d = 1/8$, and scale the galaxies to have identical *total* mass. Lacking information on the observed stellar velocity dispersion in LSB disks, we initialize velocities in *both* galaxy disks such

that Q=1.5. This conservative assumption implies lower velocity dispersion in the LSB disk, as might be expected if disk surface density determines the stellar velocity dispersion. If velocity dispersions in LSB disks are comparable to those in HSB disks, LSB galaxies will be have a higher Q and be more stable than our models. Our simulation is thus a conservative test of LSB stability. In the stellar dynamical models shown here, each halo is represented by 131,072 particles, while the disks are comprised of 32,768 particles each. The large number of halo particles used minimizes that the growth of instabilities due to discreteness noise in the halos (see, e.g., Walker, Mihos, & Hernquist 1996).

Figure 2 (Plate X) shows the evolution of the disks in the HSB-LSB interaction, viewed in the orbital plane. Closest approach occurs at T=24, and the galaxies respond quite strongly to the interaction, showing oval distortions and tidal arms shortly after the encounter. In the HSB disk, the self-gravity of the disk amplifies the perturbation such that by T=44 the galaxy has developed a very strong bar. This bar persists to the end of the simulation (T=80), significantly heating the inner disk. By contrast, the response of the LSB disk is milder, although still quite significant. The encounter strongly perturbs the galaxy, but without adequate self-gravity in the disk, no bar develops during the simulation. Instead, the LSB disk displays long-lived spiral arms and rings in the disk, and a persistent oval distortion. The crispness of the features in the LSB disk are attributable to the low velocity dispersion corresponding to Q=1.5. If, instead, the velocity dispersion in LSB disks is comparable to that in HSB disks, the sharpness of these features will be reduced, similar to those in the simulated HSB disk.

To quantify the response of the galaxies to the interaction, Figure 3 shows a Fourier analysis of the growth of the $m = 2$ mode in the inner half mass of each disk. The LSB galaxy actually responds first; due to its shallower potential well, the disk is more easily distorted by the approaching companion. After the encounter, the LSB disk settles into equilibrium, with A_2 relatively constant thereafter.[5] Because of the high dark matter content of the LSB disk galaxy, any subsequent evolution in the $m = 2$ component will occur very slowly, if at all. Meanwhile, the growth of the $m = 2$ mode in the HSB galaxy is more dramatic, as the bar continues to grow due to the disk self-gravity. The peak strength in A_2 is more than twice that of the LSB disk, and declines at late time, probably due to disk heating by the bar. We emphasize that the $m = 2$ mode is not only different in strength between the disks, but also in character: the HSB sports a strong bar, while the LSB displays a milder oval distortion. The influence of these features on the structural and hydrodynamic evolution of the galaxies will be quite different.

[5] A_2 is the amplitude of the $m = 2$ Fourier coefficient; see Sellwood & Athanassoula (1986).

5. Discussion

Both analytic arguments and numerical simulation indicate that, despite their seemingly fragile nature, LSB disks are quite stable against the growth of bar instabilities. Their low disk surface density and high dark matter content deprives LSB galaxies of the disk self-gravity necessary to amplify any nonaxisymmetric dynamical seeds. The stability of these galaxies helps explain the rarity of observed bars in LSB disks.

The stability of LSB disks also has interesting ramifications for scenarios involving LSB galaxy evolution. Although the simulations reported here are purely stellar-dynamical, preliminary models which include hydrodynamics show that without the driving force of a bar, there is no strong inflow of gas to the galaxy center. This is a problem for the otherwise appealing notion that LSB dwarf galaxies are the progenitors of H II galaxies experiencing central starbursts (Taylor et al. 1994), if tidal encounters drive gas inflow. The need for an LSB progenitor population (McGaugh 1996b) and the similarity of the environments of LSB and H II galaxies (Salzer 1989; Telles & Terlevich 1995) strongly suggests such a connection, but even the relatively close, strong interaction we have presented will not result in a strong central starburst. In order to provoke a violent enough response in the LSB disk, a bona-fide merger may be necessary. Furthermore, we have modeled rather large galaxies; the lower luminosity galaxies which are potential H II galaxy progenitors are even more dark matter dominated than our models, making it extremely difficult to drive the instabilities and radial inflows which trigger central starbursts.

Another proposed evolutionary scenario appeals to the fragility of LSB disks as an explanation for the low density environments in which these galaxies are found. LSB disks avoid high density regions, and are particularly isolated on small (< 2 Mpc) scales (Bothun et al. 1993, Mo et al. 1994). The fragile appearance of LSB disks has lead to the idea that LSBs in dense environments might be destroyed or structurally altered beyond recognition, or that star formation induced by tidal encounters may transform LSBs into HSBs. The dynamical arguments presented here indicate that LSBs are sufficiently stable to survive galaxy encounters structurally intact. However, while LSBs are robust against global instabilities, the sharp spiral features which form may correspond to *local* compressions which could push disk gas above some critical threshold and ignite star formation throughout the disk, and perhaps lead to surface brightness evolution which transforms LSBs into HSB galaxies.

A number of considerations, however, argue against the transformation of LSBs into HSBs via tidal encounters. Having modeled a strong interaction, it is not certain that more distant encounters can drive any significant perturbations. While mergers may drive more dramatic evolution, the isolation of LSBs occurs on large scales, apparent out to at least 1

Mpc. It is hard to understand how such stable galaxies can be affected at such enormous ranges since the severity of encounters declines strongly as the impact parameter increases. Moreover, any global enhancement of the surface brightness can not be so severe as to remove a galaxy from the Tully-Fisher relation, so the evolution hypothesized to explain the lack of LSBs in dense regions is probably not sufficient to fully transform their identity from LSB to HSB. Interactions may neither destroy these late type systems (as advocated by Moore et al. 1996), nor transform them structurally into systems like the Milky Way.

We are thus left with a serious conundrum. The isolation of LSB galaxies and their potential role as the progenitors of H II galaxies is qualitatively well explained by tidally induced star formation. Quantitative analysis suggests that the dark matter domination of LSB disks makes these fragile-looking galaxies surprisingly stable and resistant to this process. It may thus be that isolation is a prerequisite for the *formation* of LSB galaxies. Yet the environmental connection remains compelling and warrants further investigation.

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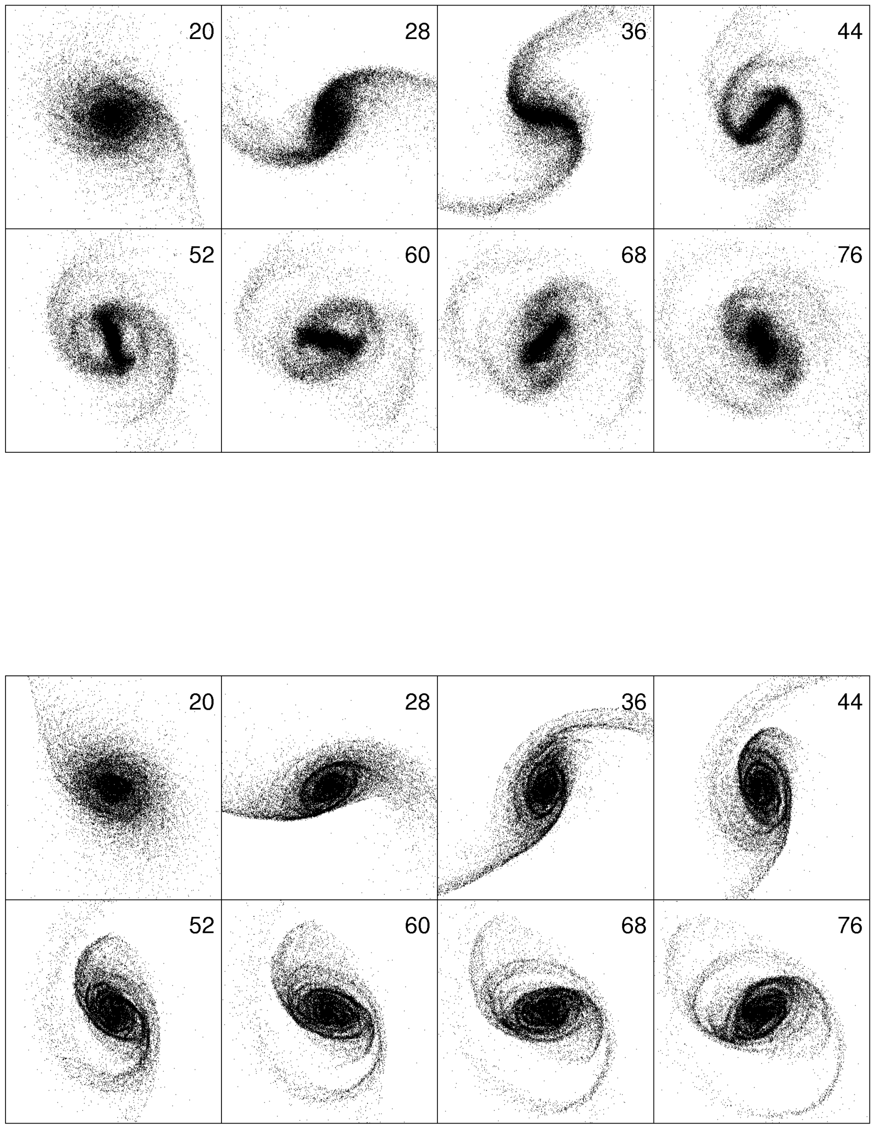

Fig. 2.— Evolution of the HSB (top) and LSB (bottom) disk during an equal (total) mass galaxy encounter with $R_{peri} = 10$ scale lengths. Each frame measure 7.5 scale lengths on a side, and time is given in the upper right corner. One half-mass rotation period is roughly 13 time units.

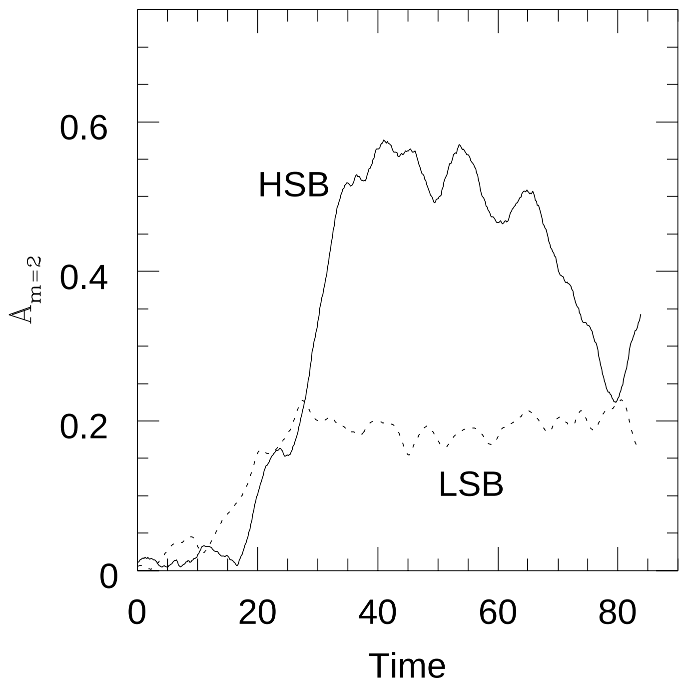

Fig. 3.— Growth of $m = 2$ modes in the HSB and LSB disk during the encounter. Closest approach occurs at $T = 24$.

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